PERFORMANCE IMPROVEMENT OF PEMFC BASED ON REDUCING SIZE OF THE SQUARE FLOW CHANNEL: A 3D CFD APPROACH

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ABSTRACT

Proton exchange membrane fuel cells (PEMFCs) have significant potential to generate clean, renewable and sustainable energy and reduce emissions to mitigate climate change. PEMFCs comprise distinct components, namely, anode and cathode bipolar plates with flow channels, catalyst layers, gas diffusion layers and a membrane. The shape of gas flow channels affects the flow velocities, gas species mass fractions and cell performance. In this study, a three-dimensional computational model is improved via the PEMFC module of ANSYS FLUENT software. The square channel configurations with widths and depths ranging from 0.2 to 0.8 mm are generated by modifying the reference channel having 1 mm depth and width. The results showed that reducing dimensions of the square channel augmented the current density due to enhancing flow velocity in the anode and cathode channels with the disadvantage of an elevated pressure drop. The configuration having a 0.2 x 0.2 mm square channel enhances the current density to 2.95 A/cm^2 compared to the reference case with a current density of 1.25 A/cm^2 at 0.4 V. But, taking into account pressure loss along the flow channels, a 0.4 x 0.4 mm square channel enhancing current density with a rise of 68% in comparison the base case at 0.4 V is a good option to improve the cell performance.

Keywords: PEMFC, CFD, Channel cross-sectional dimensions, Current density, Pressure drop.

Introduction

Fossil fuels are carbon based fuels such as crude coal, natural gas and oil which are the primary energy sources for the power generation. But they are non-renewable and burning them leads to emissions (CO_2, NO_x, particles, etc.) which cause the climate change and have the worst effects on the environment and our health. Therefore, researchers have been improving new technologies on generating alternative power sources. Fuel cells are the encouraging power sources since they are energy converters which transform the fuel chemical energy to electricity with simplicity, high power, low pollution and quiet, (Barbir, 2013). The PEM fuel cells (PEMFCs) have key advantages in comparison to other types such as low operating temperature, durability for a long lifetime, high energy density and a wide power range (Wu, 2016). These benefits favor PEMFCs for distinct applications, such as transportation, portable and backup power applications (Spiegel, 2008).

A PEMFC is a multi-part device consisting of the bipolar plates with flow channels engraved and a membrane electrode assembly (MEA) consisting of a membrane, diffusion layers (GDLs) catalyst layers (CLs) at anode and cathode (Xing, 2019). The bipolar plate distributes hydrogen and oxygen throughout the channel. H_2 molecules are broken down into electrons and protons at the anode CL. Protons moves toward the membrane whereas electrons travel to the cathode current collector by the electrical circuit. The electricity, water and waste heat are generated with combining electrons, protons and oxygen molecules at the cathode CL.

The flow channels are very crucial for the enhancement of the cell performance. Their shapes affect the distributions of gas species at the reacting area. Namely, the channel geometry determines the reactant supply to anode and cathode CL where the electrochemical reactions happen. But the geometrical modifications of the channels also impact pressure drop through the channel. Researchers have analysed the impacts of altering the channel shapes on the augmentation of PEMFC efficiency.

Cooper et al. (2017) examined the influence of the length-to-width ratio of channels having interdigitated flow fields on PEMFC performance improvement. It was seen that decreasing the aspect ratio by reducing the channel length led to higher overall performance. Chowdhury et al. (2017) found that both channel and land widths were equally significant to enhance the current density and the flow channel with 1 mm channel and

land width could be best choice regarding pressure drop and current density in the channel. Carcada et al. (2021) scrutinized the impact of the serpentine channel numbers (7, 11, and 14) and cross-sectional size on performance of PEMFC having a large active area. Their results demonstrated that a rise in number of serpentine channels or a decrease in the channel width to land width improved the cell performance, particularly at high current density. Kaplan (2021) scrutinized 15 case studies gained by modifying the width and depth of the flow channel (0.2-1.6 mm) for 1 mm constant depth and width. The findings indicated that current density and velocity in the flow channel augmented with decreasing depth and width of the channel compared to base case with the channel cross-section of 1 x 1 mm (channel width x depth) at the cost of high pressure loss.

Brakni et al. (2023) examined the impact of distinct flow field channels having constriction and widening sections at the middle of the channel on the PEMFC performance. They noticed that the configuration with a constricting hydraulic diameter of 50% showed better performance due to this configuration enhancing fluid velocity and thus more uniform velocity distribution but higher pressure loss. Dong et al. (2024) improved a three-dimensional (3D) model to study the mass transport features and performance of the cell with novel two-block structures inside the channel at the cathode. Their findings revealed that the novel two-block structures augmented oxygen concentration thanks to convection influence of these structures and thus enhanced PEMFC performance with a slight increase in pressure drop.

The goal of the current work is to examine the influence of the distinct square flow channel cross-sections on the PEMFC performance.

Materials and Methods

The 3D geometric model employed in this work is built with the help of SOLIDWORKS software. After this, the structured mesh is produced using Sweep Method in ANSYS Meshing.

The model comprises of a membrane anode and cathode CLs, GDLs, flow channels and current collectors to determine physical domains included in the Fuel Cell module (ANSYS, 2011) in Figure 1. Different configurations are obtained by decreasing the base flow channel depth and width from 1 mm to 0.2 mm with an interval of 0.2 mm in Figure 2.

The geometrical features utilized in the CFD analysis in Table 1 are based on the experimental study performed by Wang et al. (2003).

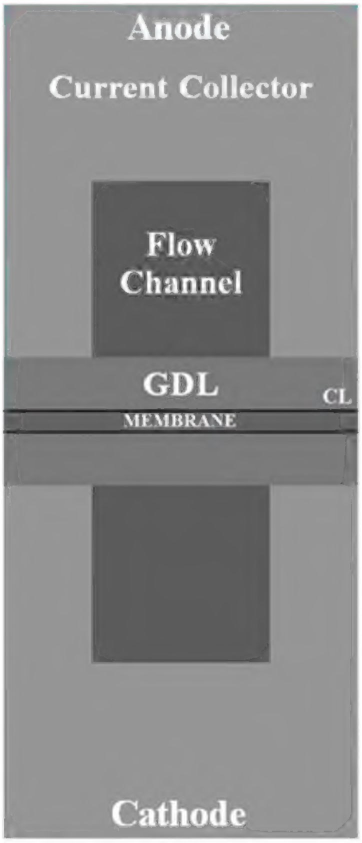

Figure 1. Cross-sectional view of PEMFC model

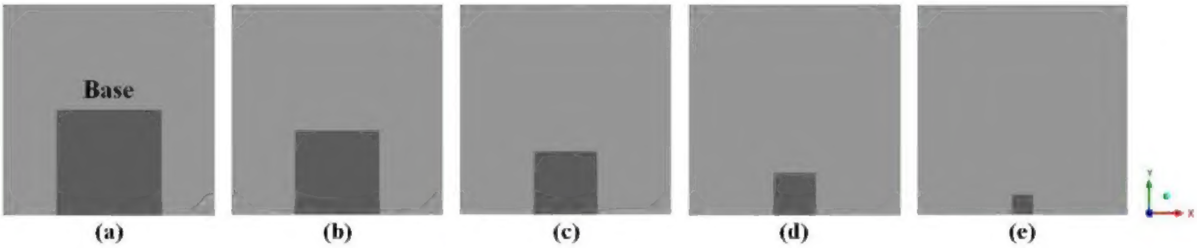

Figure 2. Flow channel configurations: a) base (1 x 1 mm), b) 0.8 x 0.8 mm c) 0.6 x 0.6 mm d) 0.4 x 0.4 mm e) 0.2 x 0.2 mm

Table 1. The geometrical characteristics of the model

Parameter	Value	Unit
Membrane	108	µm
CL thickness	12.9	µm
GDL thickness	300	µm
Channel width	1	mm
Channel height	1	mm
Cell width	2	mm
Cell length	70	mm

The parameters and operating conditions employed in the CFD analysis are listed in Table 2.

Table 2. Features and operating conditions used in the 3D CFD simulation

Parameter	Value	Uni
GDL and CL viscous resistance (Kahveci and Taymaz, 2018)	1 x 10^{12}	1/m
GDL and CL porosity (Kahveci and Taymaz, 2018)	0.5	-
CL surface/volume ratio	200000	1/m
Reference exchange current density (anode and cathode)	4000 and 0.1	A/
Anodic and cathodic transfer coefficient at anode and cathode (Wang et	0.5 and 2	-
Anode inlet mass flow rate (Kaplan, 2022a)	5.40 x 10^{-6}	kg/s
Cathode inlet mass flow rate (Kaplan, 2022a)	3.29 x 10^{-5}	kg/s
Anode inlet H_2 and H_2O mass fraction (Kaplan, 2022b)	0.2 and 0.8	-
Cathode inlet O_2 and H_2O mass fraction (Kaplan, 2022b)	0.2 and 0.1	-
H_2O and H_2 reference diffusivity (Biyikoglu and Alpat, 2011)	7.33 x 10^{-5}	m^2/
O_2 and other species reference diffusivity	2.13 x 10^{-5} and 4.9 x	m^2/
The cell temperature	343	K
Open-circuit cell voltage	0.94	V

The flow is regarded as steady state, incompressible and laminar. It is supposed that gas species behave like perfect gases. The MEA is considered as isotropic and homogenous porous media.

The equations employed in the PEMFC model are summarized in Table 3.

Table 3. The governing equations employed in the PEMFC model

Governing	Mathematical expressions
Continuity	$\nabla(\rho\vec{u}) = 0$
Momentum	$\frac{1}{(\varepsilon)^2}\nabla(\rho\vec{u}\vec{u}) = -\nabla P + \nabla(\tau) + S_m$
Energy	$\nabla(\rho c_p \vec{u} T) = \nabla(k^{eff}\nabla T) + S_e$
Species	$\nabla(\vec{u}C_i) = \nabla(D_i^{eff}\nabla C_i) + S_i$
Charge	$\nabla(\sigma_{mem}\nabla\phi_{mem}) + R_{mem} = 0,\ \nabla(\sigma_{sol}\nabla\phi_{sol}) + R_{sol} = 0$

The constant mass flow rates whose values given in Table 2 are assigned the flow channel inlets at the anode and cathode. Atmospheric pressure is specified for the flow channel outlet at the anode and cathode. All other faces are wall boundary conditions. Top faces of anode and cathode current collectors are specified as terminals. The potentials of anode and cathode terminals are 0 V and 0.39-0.92 V for the validation of the CFD model.

Findings and Discussion

The PEMFC model is validated using the measured data obtained by Wang et al. (2003) in Figure 3.

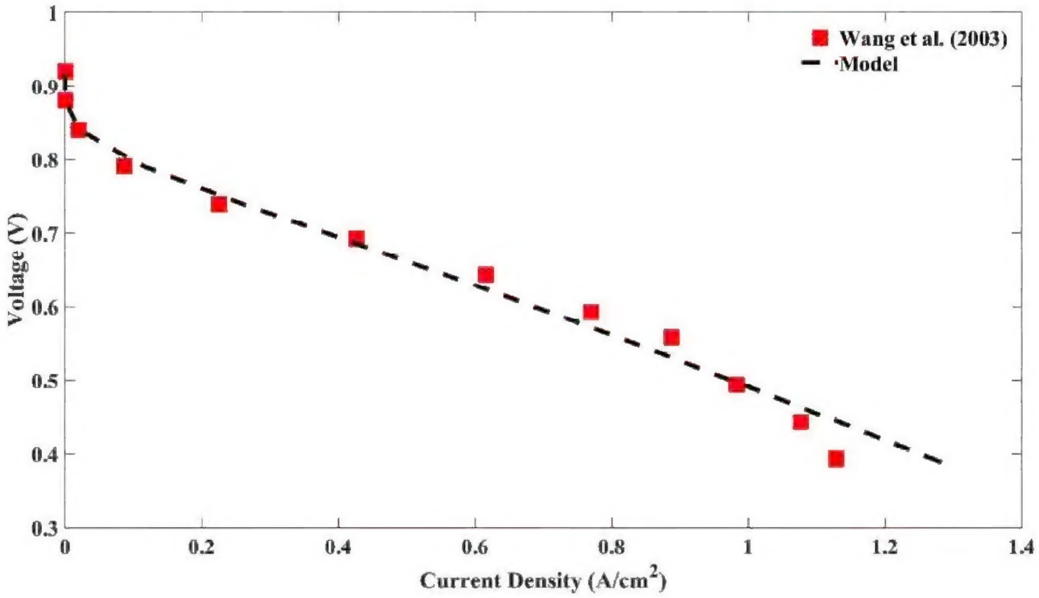

Figure 3. Validation of the PEMFC model with the measured data (Wang et al., 2003)

As illustrated in Fig. 3, the estimated results gained by the PEMFC model are a well agreement with experiment, especially at lower and medium current densities whereas the overprediction is observed at higher current densities. This is probably due to the current model not considering water (liquid) presence in the porous layers which leads to decreasing the porosity of the layers and augmenting species mass transfer resistance. Figure 4 shows the estimated current densities for the variation of the depth and width of the channels between 0.2 and 1 mm at 0.4 and 0.6 V.

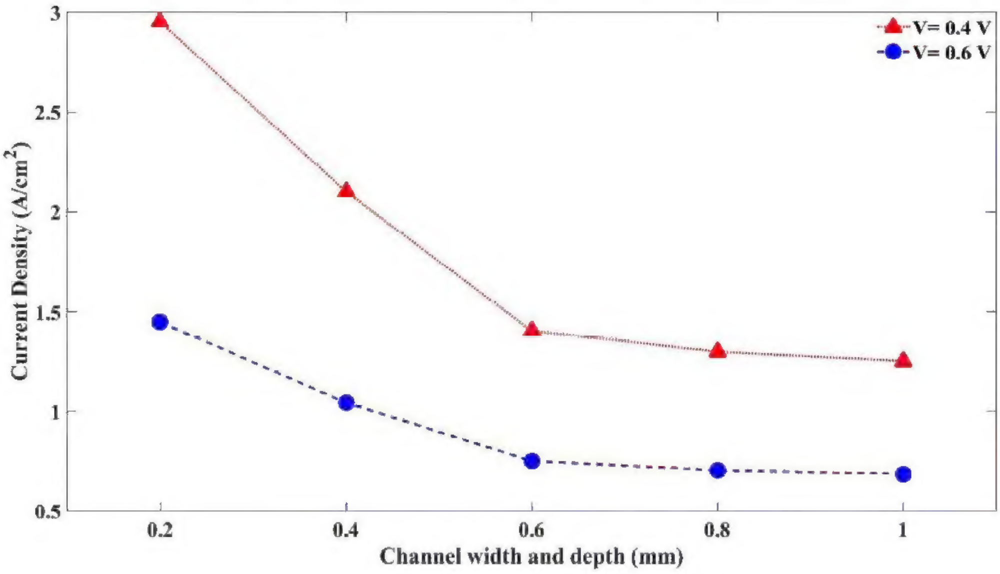

Figure 4. Change of current density as a function of channel width and depth at 0.4 and 0.6 V

The current density slightly increases between 0.6 and 1 mm channel width and depth in Figure 4. After this, current density considerably enhanced with a decrease in channel width and depth from 0.6 to 0.2 at 0.4 and

0.6 V. Therefore, the maximum current densities of 2.95 and 1.45 A/cm^2 are gained with the configuration with the channel cross-section of 0.2 x 0.2 mm at 0.4 and 0.6 V, respectively.

Figure 5 illustrates the oxygen mass fraction contours in the cathode flow channel, GDL and CL at the middle of the cell length for square channels whose cross sections of 1 x 1 mm (the base) and 0.2 x 0.2 mm at 0.4 V.

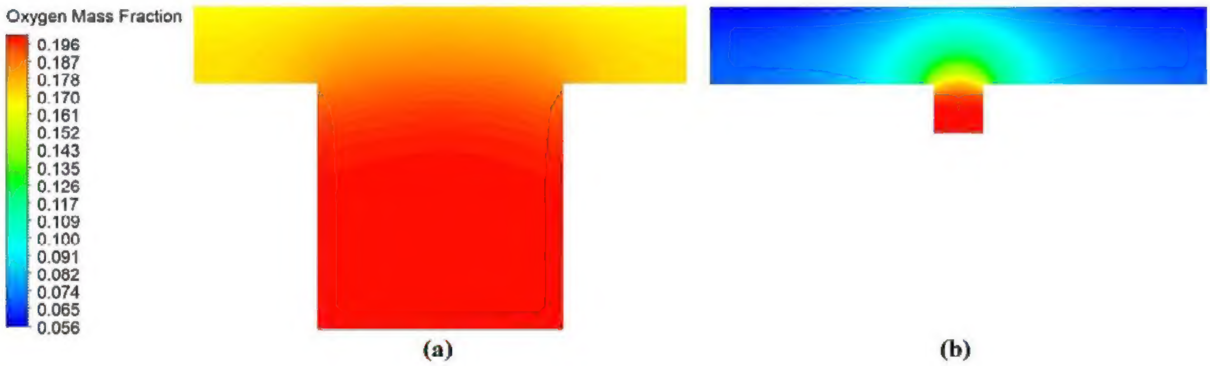

Figure 5. Oxygen mass fraction contours in the cathode flow channel, GDL and CL at the midpoint of the cell length for channel sizes of (a) 1 x 1 mm (the base) and (b) 0.2 x 0.2 mm

It is clear in Figure 5 that decreasing channel width and depth to 0.2 mm increases consumption of oxygen in CL and GDL in comparison to the base case at 0.4 V. Since 0.2 x 0.2 mm channel cross-section case produces higher current density in Figure 4, it consumes more oxygen for the reaction in the cathode CL in comparison to the base case at 0.4 V.

Figure 6 demonstrates the water mass fraction contours in the cathode flow channel, GDL and CL at the middle of the cell length for square channels whose cross sections of 1 x 1 mm (the base) and 0.2 x 0.2 mm at 0.4 V.

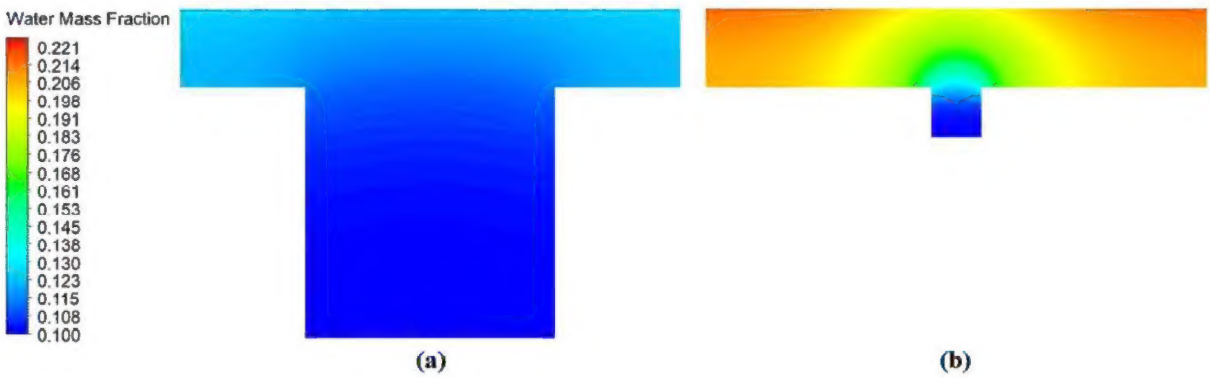

Figure 6. Water mass fraction contours in the cathode flow channel, GDL and CL at the midpoint of the cell length for channel sizes of (a) 1 x 1 mm (the base) and (b) 0.2 x 0.2 mm

It is apparent in Figure 6 that decreasing channel width and depth to 0.2 mm enhances water production in CL and GDL in comparison to the base case at 0.4 V. 0.2 x 0.2 mm channel cross-section case produces more water owing to this configuration generating higher current density in Figure 4 in comparison to the base case at 0.4 V. In conclusion, reducing flow channel cross-section dimensions leads to a decrease in oxygen and a rise in water and thus, augments the performance.

Table 4 indicates the current density and pressure drop results in the channels for varying square channel width and depth at 0.4 V.

Table 4. Current density and pressure drop results for different square channel configurations at 0.4V

Configurations	Current density (A/cm^2)	Pressure Drop	
		Anode (kPa)	Cathode (kPa)
Base	1.25	0.59	2.00
0.8 x 0.8 mm	1.30	1.39	4.85
0.6 x 0.6 mm	1.40	4.11	14.99
0.4 x 0.4 mm	2.10	18.74	68.21
0.2 x 0.2 mm	2.95	156.62	451.62

It is obvious in Table 4 that a decrease in the channel width and depth elevates the pressure drop in both channels. Besides the pressure drop at the cathode is much higher than that at the anode. This may be because of a mixture of gases in the channel at cathode being more complicated compared to that at the anode. The maximum current density is achieved with the configuration with 0.2 x 0.2 mm cross section but the cathode channel of this configuration produces the highest pressure drop of 451.62 kPa in Table 4. Taking into consideration pressure drop and current density in the channels, 0.4 x 0.4 mm channel case augmenting current density by 68% in comparison to the reference case at 0.4 V is better option to improve PEMFC performance.

Conclusion and Recommendations

In the present study, a 3-D numerical model is developed and validated by the measured data (Wang et al., 2003) to examine the effect of changing the square flow channel dimensions (width and depth) on PEMFC performance. The main findings are as follow:

- The lower the square channel width and depth leads to enhancing PEMFC performanceat 0.4 and 0.6 V.
- The maximum current density of 2.95 A/cm^2 is achieved with the configuration with a square channel of 0.2 x 0.2 mm cross-section at 0.4 V. Thus, in this configuration, oxygen concentration decreases and water concentration augment in the GDL and CL in comparison to the base configuration at 0.4 V.
- A reduction in dimensions of the square flow channel leads to higher pressure drop in the flow channels.
- Considering current density and pressure drop, the square channel of cross-section size 0.4 x 0.4 mm is more efficient option with 68% enhancement of the current density compared to base model provides better performance.

These outcomes emphasize the significance of the flow channel shapes in the design of efficient fuel cell systems. Future work includes the impact of distinct operating conditions and material properties on the cell performance which would improve the model suggested in this study.

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